BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

SUBJECT: AAP Electrical Power System Simulation - Case 620

DATE: January 29, 1969

FROM: B. W. Moss

ABSTRACT

A mathematical model of the AAP Orbital Assembly Electrical Power System (EPS) has been designed to permit performance evaluation when power is being transferred from the Airlock Module to the Command and Service Modules. A 56-day mission average of 475 watts will be transferred for a configuration using 2 fuel cell power plants (FCP's), each with 31 cells. The average power transfer is 480 watts using 3 FCP's of 30 cells each, and 115 watts using 3 FCP's of 31 cells each.

When maximum loads simultaneously exist in all modules of the Orbital Assembly, it is possible for the AM EPS to be overloaded by the demand for large power transfer. This condition occurs because of the voltage difference existing between CM and AM buses. To avoid this overload, it is required that the proposed larger solar array (1364 ft^2) be used and that the AM EPS voltage be adjusted throughout the mission to limit the power transferred for any given β-angle.

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MEMORANDUM FOR FILE

INTRODUCTION

The prediction of Electrical Power System (EPS) performance during power transfer between modules of the Orbital Assembly (OA) for the AAP 1-2, 3A, and 3-4 missions has been of interest for some time. Various contractors, notably North American Rockwell (NAR) and McDonnell Douglas Corporation (MDC), are performing simulations of primarily those portions of the EPS in which their particular interest lies. As a result, the performance of the total system has not received the consideration it deserves. A meeting held recently at MSC (Ref. 1), which included NAR and MDC, had as its purpose the interchange of information on the simulations each contractor is running and the integration of both simulations to result in one overall system model.

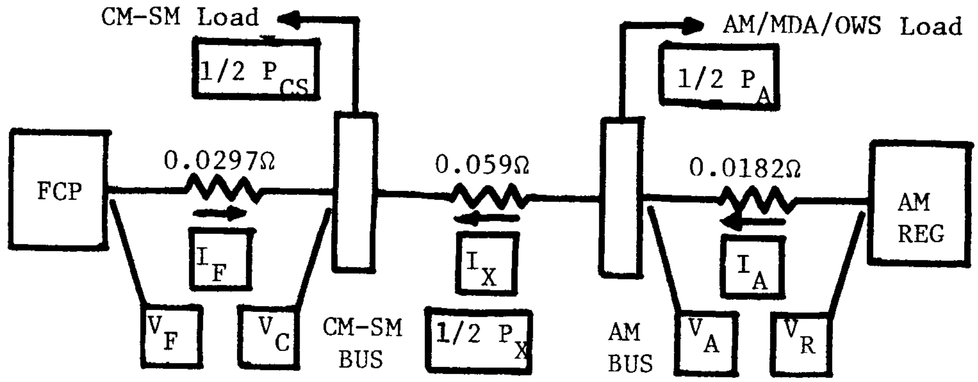
To gain a better understanding of the overall EPS performance, models have been devised at Bellcomm to permit performance evaluation as a function of various system parameters. Of particular interest is the amount of power transferred between the AM EPS and the CM-SM EPS.

MODEL DESIGN

Using data on cabling resistance (Ref. 2), two models were designed; the Combined Bus Model (Fig. 1) considers CM and SM buses as one bus and the Separate Bus Model (Fig. 2) considers these buses separately. In both models, each module is considered to have two identical, equally loaded buses, only one of which is shown. The Combined Bus Model is simpler but assumes an even split between CM and SM loads, which may not necessarily be correct. Further, the capability for predicting CM and SM bus voltages and for changing CM and SM loads is lost. The power losses in the CM to AM interconnecting cabling is ignored for this first approximation -- it is about 2.5% under maximum power transfer and much less under nominal power transfer conditions.

LINE RESISTANCES

The values used in the various models for the line resistances are shown in Table I. The values shown are applicable to each of the two identical buses. For the Combined Bus Model, the CM bus to FCP line resistance is exactly the sum of half the SM bus to CM bus resistance and the FCP to SM bus resistance. This is true, however, only for the assumption of equal CM and SM loads.



P_X = Transferred power, watts

$\frac{P_A}{2}$ = AM bus load = $\frac{\text{AM/MDA/OWS load}}{2} = \frac{2882}{2}$ watts

$\frac{P_C}{2}$ = CM-SM bus load = $\frac{\text{CM/SM load}}{2} = \frac{2250}{2}$ watts

V_R = AM regulator no-load voltage = 30.0 volts

(Ref. 3) V_F = FCP voltage = $[1.2845 - 0.0002\ I_F - 0.0352(47.3+I_F)^{\frac{1}{2}} - Dt]\ N$

I_F = FCP current = I_{CS} (2 FCP)

$= \frac{2}{3}\ I_{CS}$ (3 FCP)

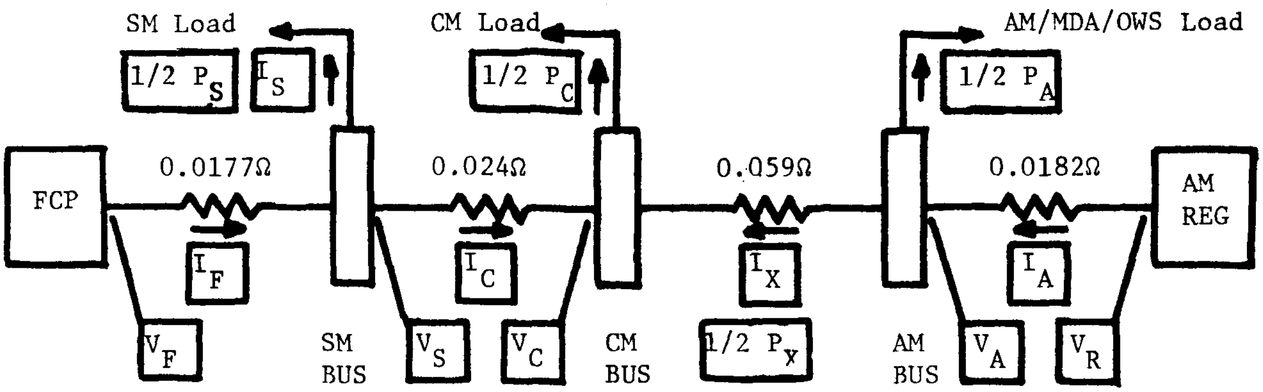
D = degradation rate = 30 mv/hr/cell

t = total time FCP has been in operation, hrs

N = number of cells/FCP

COMBINED BUS MODEL

FIGURE 1



P_X = Transferred power, watts

$\frac{P_A}{2}$ = AM bus load = $\frac{\text{AM/MDA/OWS load}}{2} = \frac{2882}{2}$ watts

P_C = CM load

P_S = SM load

V_R = AM regulator no-load voltage = 30.0 volts

V_F = FCP voltage = $[1.2845 - 0.0002\ I_F - 0.0352(47.3+I_F)^{\frac{1}{2}} - Dt]\ N$

I_F = FCP current = $I_C + I_S$ (2 FCP)

$= \frac{2}{3}(I_C + I_S)$ (3 FCP)

D = degradation rate = 30 mv/hr/cell

t = total time FCP has been in operation, hrs

N = number of cells/FCP

SEPARATE BUS MODEL

FIGURE 2

Line Resistances

(milliohms)

	NAR (Ref. 1)	MDC (Ref. 2)	Bellcomm (Fig. 1&2)
AM Reg. to AM bus	18.20	19.82	18.20
AM bus to CM bus	28.6(1)	56.2	59.0(2)
CM bus to SM bus	21.6	24.0	24.0
SM bus to FCP	14.3	17.7	17.7

(1) Does not include line resistance from MDA docking port to AM bus.

(2) Reference 4.

TABLE I

COMBINED BUS MODEL

The relations that must exist for the system (Fig. 1) are given below:

$$V_A = V_R - 0.0182\, I_A$$

The equivalent resistance between the AM regulators and AM bus of 0.0182 ohms (Ref. 1) includes the effect of regulator droop (40 mv/amp/reg) and the stated line resistance. Since four regulators are in parallel for each bus, the droop becomes 10 mv/amp or 0.010 ohms. The current is then determined by considering half the total load on each of the two buses. Hence,

$$I_A = \frac{P_A+P_X}{2V_A}$$

So, $$V_A = V_R - 0.0182\, \frac{P_A+P_X}{2V_A}$$

By the quadratic equation,

$$V_A = \frac{V_R + \sqrt{V_R^2 - 0.0364\,(P_A+P_X)}}{2} \qquad (1)$$

The voltage at the combined CM-SM bus due to the AM bus must be

$$V_C = V_A - 0.059\, I_X$$

The transferred current for each of two buses is half the total

$$I_X = \frac{P_X}{2V_C} \qquad (2)$$

So, $$V_C = V_A - 0.059 \frac{P_X}{2V_C}$$

Application of the quadratic equation yields

$$V_C = \frac{V_A + \sqrt{V_A^2 - 0.118\ P_X}}{2} \tag{3}$$

From this, we can determine the current supplied to the CM-SM bus from the fuel cell power plants (FCP) in the SM.

$$I_{CS} = \frac{P_C - P_X}{2V_C} \tag{4}$$

The current from each FCP depends on whether two or three FCP's are operating

$$I_F = I_{CS} \quad \text{if 2 FCP's operate} \tag{5.0}$$

$$\text{or} \quad I_F = \frac{2}{3} I_{CS} \quad \text{if 3 FCP's operate} \tag{5.1}$$

Now, the voltage required at the FCP output for the conditions specified must be

$$V_F = V_C + 0.0297\ I_F \tag{6}$$

But the voltage out of the FCP is determined by the electrochemical reaction, the current density, the total operating time, the temperature, and the number of cells per FCP. This is given by the following expression from Ref. 3:

$$V_F = [1.2845 - 0.0002\ I_F - 0.0352\ (47.3 + I_F)^{\frac{1}{2}} - Dt]\ N \tag{7}$$

V_F as determined by (6) and by (7) must be equal. The power transferred, P_X, is the result in which we are interested for various combinations of the parameters P_A, P_C, D, N, and time, and an iterative process must be used for each case.

SEPARATE BUS MODEL

The separation of CM and SM buses will not affect the relationships previously developed for the AM bus. Hence, equations (1), (2), and (3) are simply repeated here

$$V_A = \frac{V_R + \sqrt{V_R^2 - 0.0364\ (P_A+P_X)}}{2} \quad (1)$$

$$I_X = \frac{P_X}{2V_C} \quad (2)$$

$$V_C = \frac{V_A + \sqrt{V_A^2 - 0.118\ P_X}}{2} \quad (3)$$

The current flowing to the CM bus from the SM bus must be

$$I_C = \frac{P_C - P_X}{2V_C} \quad (8)$$

The voltage at the SM bus is

$$V_S = V_C + 0.024\ I_C \quad (9)$$

The current flowing to the SM loads is

$$I_S = \frac{P_S}{2V_S} \quad (10)$$

and the total current supplied by a FCP is

$$I_F = I_C + I_S \quad \text{if 2 FCP's operate} \tag{11.0}$$

or $$I_F = \frac{2}{3}(I_C + I_S) \quad \text{if 3 FCP's operate} \tag{11.1}$$

The voltage required at the FCP output for the conditions specified must be

$$V_F = V_S + 0.0177\, I_F \tag{12}$$

But the voltage out of the FCP again is given by

$$V_F = [1.2845 - 0.0002\, I_F - 0.0352\, (47.3 + I_F)^{\frac{1}{2}} - Dt]\, N \tag{7}$$

V_F as determined by (12) and by (7) must be equal.

RESULTS

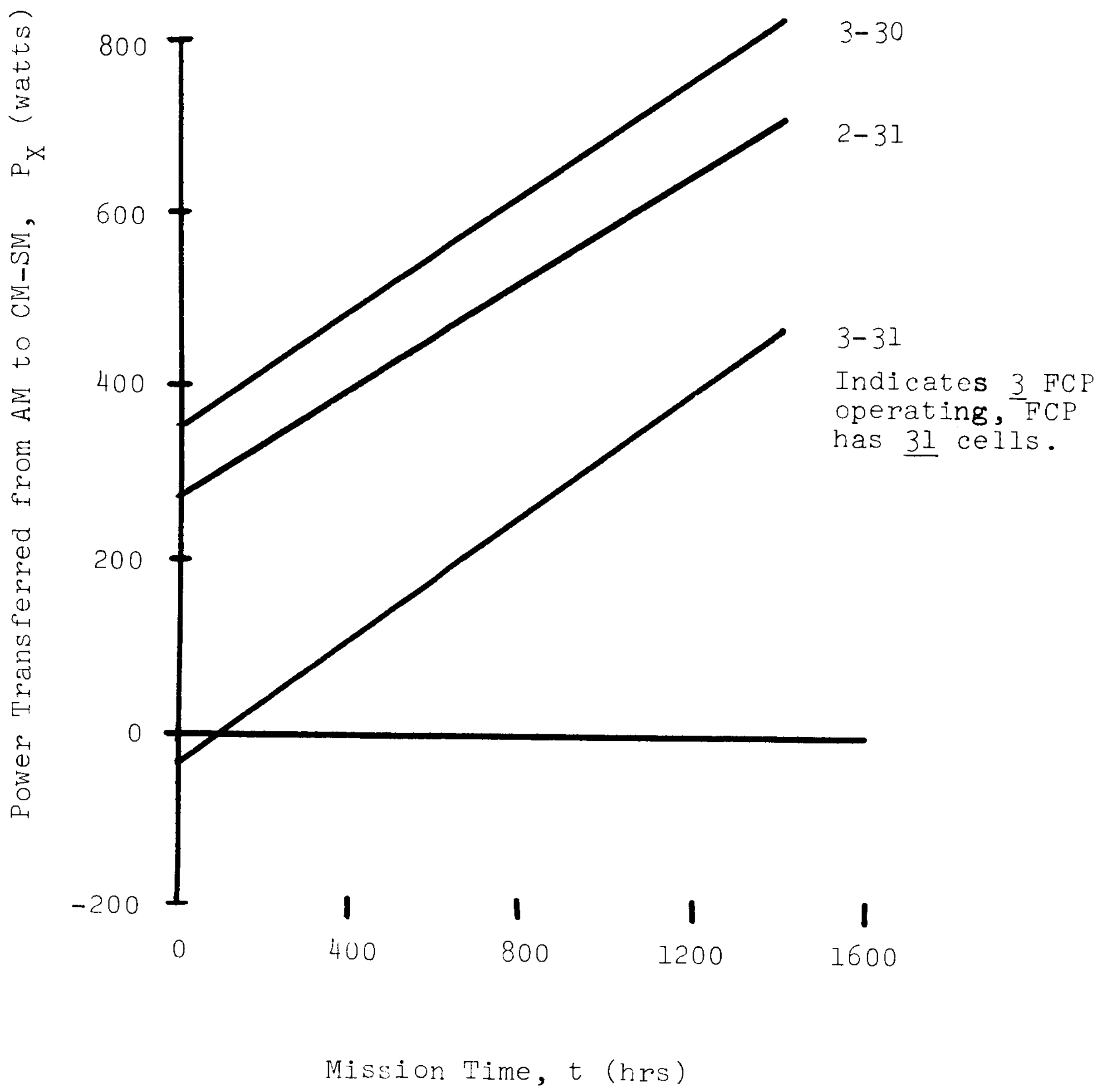
Using the two models, determinations were made of the power transferred as a function of time for three different FCP configurations. Mission average power requirements of 2250 watts for the CM-SM (P_C) and 2882 watts for the AM (P_A) were used. The results are shown on Table II. A plot of these data is shown in Fig. 3 for the Combined Bus Model and in Fig. 4 for the Separate Bus Model.

The results suggest that a system configuration using two 31-cell FCP's or three 30-cell FCP's will yield approximately the same power transfer over the mission lifetime using mission average power for the modules. In the event of a FCP cell failure during the mission, however, the two 31-cell configuration will permit use of the third fuel cell for continuation of the mission. However, in the event of a FCP failure, the three 30-cell configuration would require reduction of loads to avoid overloading of the AM EPS by power transfer. Further, the two 31-cell fuel cell configuration permits use of the third fuel cell for periods of peak load.

Model		Hrs. t	Volts V_A	V_C	V_S	V_F	Amps I_X	I_F	Watts P_A	P_C	P_S	P_F	P_X	P_T
2-31	CB	0	29.009	28.726		29.746	4.804	34.359	2882	2250		2044	276	5202
		1400	28.866	28.115		28.925	12.733	27.281	2882	2250		1574	716	5172
	SB	0	29.017	28.760	29.125	29.736	4.364	34.508	2882	1125	1125	2052	251	5185
		700	28.949	28.472	28.752	29.305	8.078	31.242	2882	1125	1125	1831	460	5173
		1400	28.882	28.186	28.382	28.877	11.797	27.979	2882	1125	1125	1616	665	5163
3-31	CB	0	29.110	29.144		30.306	0.584	26.150	2882	2250		2378	-34	5260
		1400	28.945	28.455		29.382	8.311	20.817	2882	2250		1835	473	5190
	SB	0	29.140	29.269	29.782	30.257	2.179	26.850	2882	1125	1125	2437	-127	5319
		355	29.099	29.099	29.563	30.016	0	25.572	2882	1125	1125	2303	0	5185
		700	29.059	28.935	29.351	29.782	2.108	24.331	2882	1125	1125	2174	122	5178
		1400	28.980	28.604	28.923	29.309	6.380	21.822	2882	1125	1125	1919	365	5166
3-30	CB	0	28.985	28.622		29.605	6.149	22.104	2882	2250		1963	352	5197
		1400	28.829	27.954		28.709	14.828	16.945	2882	2250		1460	829	5171
	SB	0	29.019	28.766	29.132	29.540	4.293	23.047	2882	1125	1125	2042	247	5171
		1400	28.868	28.123	28.300	28.622	12.623	18.169	2882	1125	1125	1560	710	5152

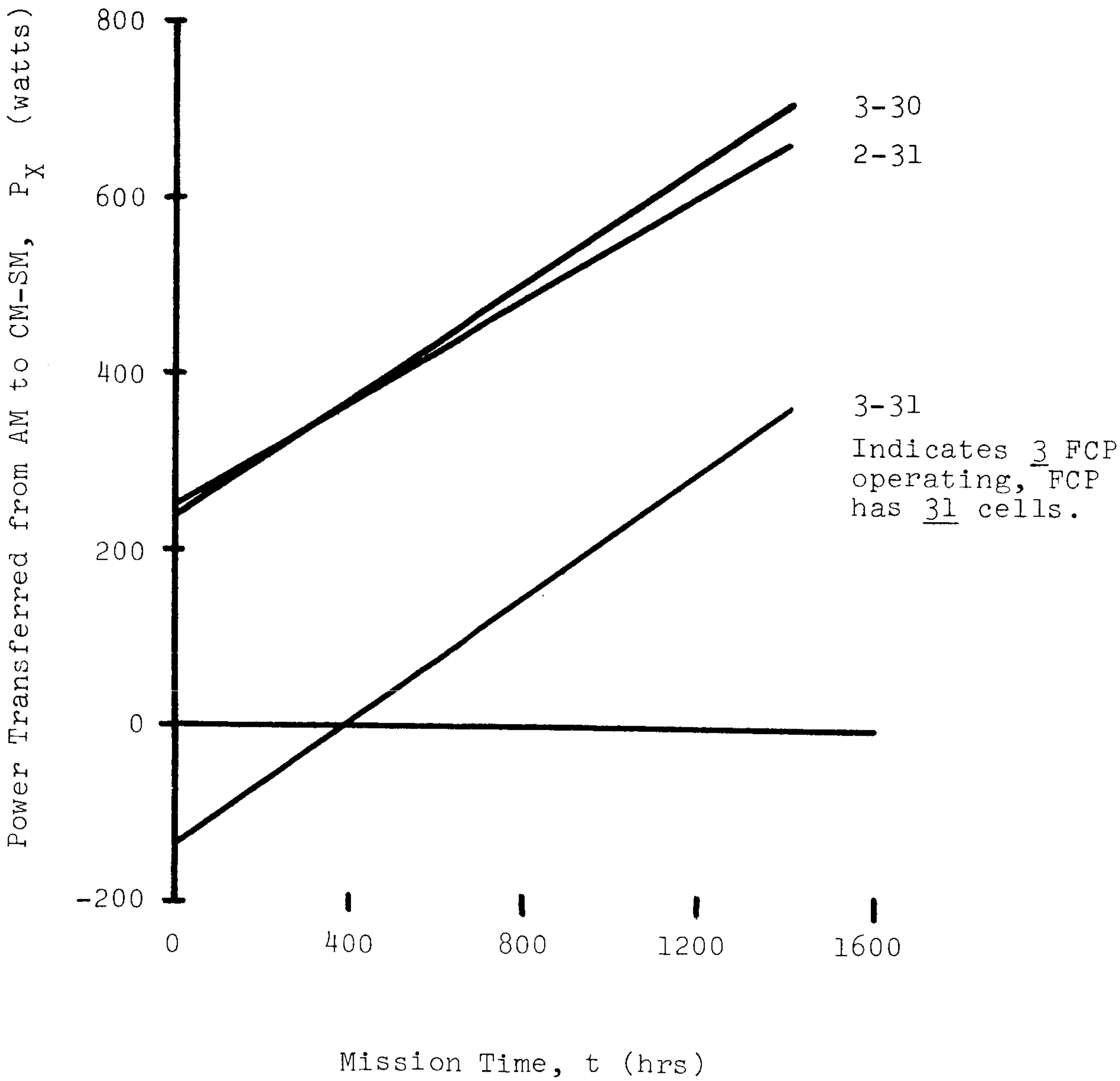
$$P_T = P_A + P_X + P_F$$
$$= P_A + P_C + P_S + \text{losses}$$

TABLE II



COMBINED BUS MODEL

FIGURE 3



SEPARATE BUS MODEL

FIGURE 4

In order to evaluate system performance at off-nominal points, i.e., with loads other than mission average loads, a minimum system power and maximum system power condition were postulated. The conditions and results are as shown on Table III. At the maximum power condition with 3 FCP's operating, the AM EPS will be overloaded with the requirement to supply its loads (P_A = 3111) and to transfer 1045 watts to the CM-SM EPS. It must be remembered, however, that the power capability rating for the AM EPS is based on $\beta = 0^\circ$*, i.e., minimum power capability. Two conditions could cause this capability to be improved -- the use of the proposed new solar array (Ref. 5) with minimum power rating of 4100 watts instead of 3500 watts and/or β-angle other than 0° for the mission time corresponding to the occurrence of maximum load.

PERFORMANCE IMPROVEMENT

Using the present OWS Solar Array (1200 ft^2)**, the minimum continuous bus power ($\beta = 0^\circ$) is given as 3500 watts for AAP 1-2 and 3290 watts for AAP 3-4 (Ref. 6). Using a value of the ratio of solar array power output in sunlight to continuous power delivered to the load, $P_{SA}/P_L = 2.55$ (Ref. 5), and values for subsystem efficiencies as given in Ref. 7, a value can be determined for β for which the necessary power will be available. This is summarized on Table IV and requires $\beta = 59.1^\circ$. No orbit of 210 NM altitude with an inclination of less than approximately 35.5° would ever achieve a power level sufficient to supply the postulated loads for AAP 3-4.

Using the proposed OWS Solar Array (1364 ft^2)**, the minimum continuous bus power ($\beta = 0^\circ$) is given as 4100 watts for AAP 1-2 and 3650 watts for AAP 3-4 (Ref. 5). Again, using the values of subsystem efficiencies in Ref. 7, a value can be determined for β for which the necessary power will be available. This value of β is 42.1°, which is attainable for a 210 NM orbit with inclination of 35° for periods as long as 13 days depending on launch time.

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*β is defined as the minimum angle between the solar vector and the orbital plane. For a circular orbit, a small β angle corresponds to a high percent of time in earth shadow which results in less solar array energy output.

**Discussion with H.J. Fichtner, R-ASTR-E/MSFC, on 24 January 1969, disclosed that MSFC has been authorized to proceed with the design of the larger solar array (1364 ft^2) and that this array is now considered part of the baseline configuration.

			Loads							
Case	Config.	t,hrs	P_A	P_C	P_S	P_X	P_A+P_X	P_C-P_X	P_F	P_T
Min. Total Power	2-31 FCP's	1284	2882	1155	0	113	2995	1042	1069	4064
Max. Total Power	3-31 FCP's	400	3111	2900	1100	1045	4156	2955	3109	7265

$$P_T = P_A + P_X + P_F = P_A + P_C + P_S + \text{losses}$$

Off-nominal EPS Performance

TABLE III

	Area ft^2	β°	τ_D/τ_L (2)	P_{SA}/P_L (3)	P_{SA} (Watts)	P_L (Watts)	P_R (4) (Watts)
AAP 1-2	1200	0	0.645	2.55	10270	4030	3500
AAP 3-4	1200	0	0.645	2.55	9650 (1)	3790	3290
AAP 3-4	1200	59.1	0.381	2.03	9650 (1)	4756	4156
AAP 1-2	1364	0	0.645	2.55	11900	4665	4080
AAP 3-4	1364	0	0.645	2.55	11190 (1)	4385	3790
AAP 3-4	1364	42.1	0.543	2.35	11190 (1)	4756	4156

(1) 6% solar array degradation

(2) Dark time/light time in 210 NM orbit

(3) Based on Regulator Efficiency = 0.95
Charger Efficiency = 0.95
Battery wh Efficiency = 0.68
Distribution Losses = 0.212

(4) Available bus power after allowance for bus split and regulator mismatch

AM EPS Available Power

TABLE IV

The total power supplied by the AM EPS can be limited for any given β-angle by adjustment of the regulator no-load voltage setting - increasing the voltage increases the portion of the load assumed and decreasing the voltage decreases the load assumed. The remainder of the power required for any given load condition then would be supplied by the FCP's. To avoid overloading of the AM EPS during periods of maximum power requirement such as initial pressurization, EVA, etc., the AM EPS could be loaded to its full capability for whatever β-angle existed and the FCP's would assume the remainder of the load. Operating in this manner permits complete control of the behavior of both the AM EPS and the CM-SM EPS. While this will require additional crew participation, it has the advantage of providing complete control of cryogenic reactant usage, potable water production, battery depth of discharge, and AM to CM-SM power transfer. The sensitivity of power transferred as a function of bus voltage is on the order of 350 watts/volt, i.e., a reduction of AM bus no-load voltage setting of 0.1 volt will reduce the power transferred by approximately 35 watts.

A more comprehensive model is being developed which will permit determination of complete system performance for any chosen set of system parameters. Loads as a function of time will be inserted so that a complete time history of system performance will be available. This presupposes, of course, existence of an electrical load time line for each mission. Such a time line is not now available.

CONCLUSIONS

1. A three FCP configuration with 31 cells/FCP is preferable because of improved mission reliability and greater system flexibility.

2. A method of controlling AM EPS performance during the mission is necessary for control of power transfer.

3. The larger solar array being designed by MSFC is necessary to avoid overloading the system during periods of peak load.

4. Adequate power can be transferred from the AM EPS to the CM-SM EPS (using mission average loads) to permit FCP operation at 1800 watts average.

BWMoss

1022-BWM-ms B. W. Moss

References

1. AAP Electrical Power Simulation Programs Data Interchange Meeting, Bellcomm Memorandum for File, B. W. Moss, December 4, 1968.

2. Minutes of Second AAP Power Systems Working Group Meeting, May 22, 1968.

3. AAP CSM Configuration Baseline, NAR SD 68-558, October 7, 1968.

4. Personal Communication - H. Johnson, MDC, November 14, 1968.

5. AAP Weight and Performance Review, MSFC, September 26, 1968.

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7. Minutes of AAP Baseline Review, Headquarters, February 27, 1968.

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